
AC 2012-3681: INTEGRATING THE MECHANICAL ENGINEERING CURRICULUM USING A LONG-TERM GREEN DESIGN PROJECT

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Integrating the Mechanical Engineering Curriculum using a Long-Term Green Design Project Part 1: The Hybrid Powertrain Project

Abstract

Subjects that are separate in the curriculum, such as thermodynamics and mechanical design, are integrated in practice, since thermal and mechanical systems must function cohesively in real mechanical systems (e.g. an air conditioner). With this in mind, we are beginning the implementation of a novel, potentially transformative approach to integrating coursework through five semesters of the core mechanical engineering curriculum.

The centerpiece of this research is a long-term design/build/test project that will be developed by students over the course of five semesters. The project, a bench-scale hybrid powertrain, is implemented in modules, so that parts of the project may be completed in disparate courses such as Thermodynamics, System Dynamics and Control, and Fluid Mechanics. This paper describes each module, and provides information on how the modules are integrated into a cohesive system at the end of the project.

Introduction

The authors have embarked upon a study whose goal is to study the effect of a long term hands-on design project on core concept retention. This paper describes the “hardware” portion of the research – the system to be designed and built by the students over the course of five semesters. Assessing changes (if any) in student learning forms an integral part of this research, but will be described in a forthcoming paper.

Ensuring retention of critical engineering concepts can be quite challenging. Hearing a variation on “but we never learned this!” is an all-too-frequent experience for most instructors, and many students feel justified in jettisoning all knowledge of a subject once the final examination is past. The situation is well summarized by Avitabile¹:

The unfortunate part is that as soon as the test is over or the course is completed, the students often just forget the material since they have no reason to retain the compartmentalized, modularized material.

Subjects that are separate in the curriculum, such as thermodynamics and mechanical design, are integrated in practice, since thermal and mechanical systems must function cohesively in real mechanical systems (e.g. an air conditioner). With this in mind, we propose to implement a novel, potentially transformative approach to integrating coursework through five semesters of the core mechanical engineering curriculum. The proposed work will test two hypotheses:

1. A long-term design project that integrates knowledge from multiple courses strengthens student knowledge retention.

2. A large-scale design project requiring tools from many courses improves student problem-solving and design skills.

By integrating five semesters of the mechanical engineering curriculum into a cohesive whole, this project has the potential to transform the way undergraduate education is delivered. Before and after testing will be conducted to assess a) change in retention between courses and b) change in student problem-solving and design skills.

Background

Many sources have made the case for reforming engineering education to reflect modern trends. Most notably, a recent National Academy of Engineering (NAE) report found that²

Engineering education must avoid the cliché of teaching more and more about less and less, until it teaches everything about nothing. Addressing this problem may involve reconsideration of the basic structure of engineering departments and the infrastructure for evaluating the performance of professors as much as it does selecting the coursework students should be taught.

The report also stressed the importance of teaching young engineers the merits of sustainable design⁵ and ecologically-friendly practices. The proposed work addresses two of the main concerns of the NAE report: modernization of the engineering curriculum through multidisciplinary integration and stressing “green engineering” at the design level.

Research has demonstrated several advantages of Project-Based Learning over traditional lecture methods, especially in STEM fields (see, e.g. [4]). Accordingly, we have adopted a project-based approach to integrating coursework across the mechanical engineering curriculum. A more thorough discussion of the merits of Project-Based Instruction is given in an accompanying paper⁹. The purpose of the following paper is to describe the hardware systems used to implement the project.

The authors have significant experience in developing and implementing multidisciplinary projects – especially ones that integrate distinct courses in the mechanical engineering curriculum (Mechanical Design, Thermodynamics and System Dynamics)^{5, 6, 7}. In brief, our students have designed, built and tested (in friendly competition) several large-scale design projects including an air compressor, an air powered engine (modeled on a steam engine mechanism), an air-motor speed control system, among others. Each of these projects was conducted collaboratively between two traditionally separate courses, which required close collaboration between the affected instructors.

Having this level of experience and knowledge at our disposal, we feel confident in embarking upon an even more ambitious student project: integrating five semesters of coursework through the design, fabrication and testing of a small-scale hybrid powertrain system. Informed by the latest research in project-based learning, this project will incorporate all of the lessons we have learned over the past ten years.

Overview of Proposed Work

For this work we have made the air engine project one component of a much more complicated system to be developed across a range of courses, including Machine Design, Mechanical Design, Thermal-Fluid Sciences and System Dynamics. In short, we will use the design and fabrication of a *Hybrid Electric Vehicle Powertrain*, discussed below, to integrate the majority of the core mechanical engineering courses.

Recent increases in energy costs, especially for fossil fuels, have made highly fuel-efficient vehicles very desirable. Additionally, problems associated with greenhouse gas emissions, especially global warming, demand innovative technologies. One promising solution to this crisis is the use of vehicles with hybrid gasoline/electric powertrains. Most major automobile manufacturers are now selling hybrids (most famously, the Toyota Prius) and hybrids make up nearly 3% of light-duty vehicle sales.

Unfortunately, much of the benefit of this innovative technology is lost to US engineers, since the design and development of the vehicles with the highest sales figures were done elsewhere. In fact, less than 10% of hybrid-electric vehicle sales went to US manufacturers in the years 2005–2009⁸. To regain the lead in such cutting-edge technologies, US engineering students must become more proficient in the kind of multidisciplinary design that created hybrid-electric vehicles.

The hybrid-electric powertrain project is divided into six discrete modules, each of which can be completed in a few regularly-scheduled laboratory periods. A simplified diagram of a hybrid powertrain is shown in Figure 1. The powertrain is very similar to the one used in a first-generation Toyota Prius. In this design, power is supplied to a load using an *air motor* and motor/generator. The contributions of the air motor and motor/generator are combined in the *planetary gearset*, which is in turn regulated by a second DC electric motor. The strategy employed by the *controller* is to keep the output shaft turning at a constant speed, despite variations in load. It does this by regulating the 1) air flow to the air motor, 2) the electrical flow between the battery pack and the motor/generator and 3) the speed of the sun gear in the planetary gearset.

Beginning in the Spring of 2012, the students will design and fabricate the components shown in Table 1. Each module is designed to be stand-alone; that is, students can implement the *Electric Motor Speed Control* module without having completed the *Planetary Gearset* module. But completing all the modules in sequence, it is hoped, will lead to a much deeper, broader understanding of core concepts in mechanical engineering.

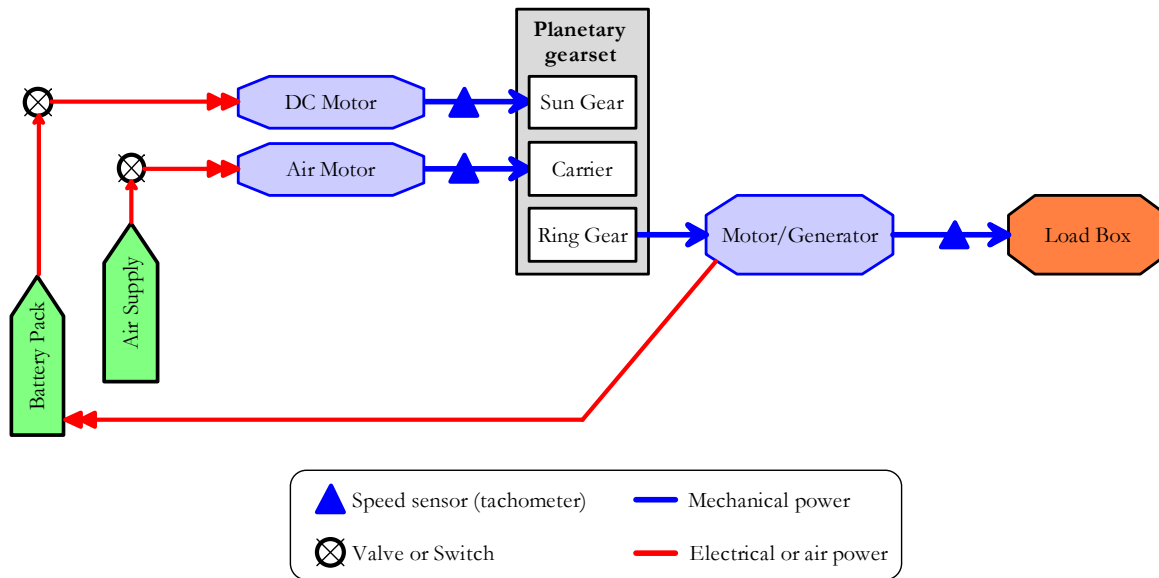


FIGURE 1: SCHEMATIC OF HYBRID-ELECTRIC POWERTRAIN

Table 1: Design/Build Project Timeline			
Semester		Course	Module
Year 1 (2011-2012)	Fall		
	Spring	ME Lab	Arduino-based tachometer
Year 2 (2012-2013)	Fall	Thermal-Fluid Sciences I Machine Design	Air-powered motor Planetary gearset
	Spring	Thermal-Fluid Sciences II	Air valve selection and implementation
Year 3 (2013-2014)	Fall	System Dynamics and Control I	Electric motor speed control
	Spring	System Dynamics and Control II	Overall control system

A Description of the Modules

A rendering of the proposed hybrid powertrain is shown in Figure 2. On the right side of the figure is the *Air Motor*, the primary source of power for the system. The air motor is driven by compressed air, whose flow rate is regulated by the *Air Flow Regulator*. At the center of the diagram is the *Motor/Generator*, which may charge the *Battery Pack* depending upon load requirements. The *Electric Motor* and the *Air Motor* serve as inputs into the *Planetary Gearset*, at the center of the diagram. The output of the planetary gearset drives the *Motor/Generator*, which is directly coupled to the *Output Shaft*. The load is an electromagnetic brake programmed to provide an interesting load cycle to the system. This type of variable load can be used to simulate the varying road load requirements of a vehicle executing a city driving cycle, for example.

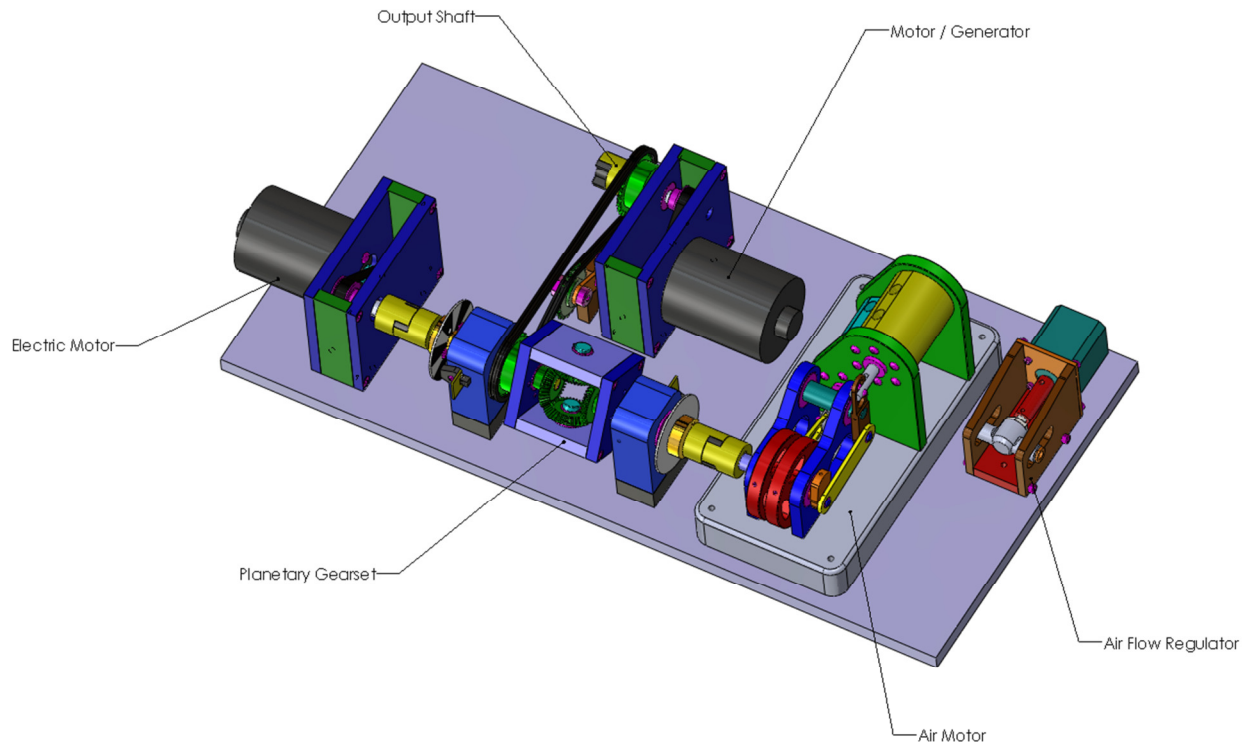


FIGURE 2: HYBRID-ELECTRIC POWERTRAIN AS IMPLEMENTED

Mounted to the planetary gearset are two tachometers that read the speeds of the three shafts entering the gearbox (the speed of the third shaft can be calculated if the other two are known). The tachometer output signals are sent to the controller, which uses this information to regulate air to the air motor (through a flow-control valve) and to regulate the power flow between motor/generator and battery pack (through high-power electronic switches). All controller components are designed around the Arduino series of microcontrollers. These are simple to use and provide an excellent introduction to modern mechatronic design.

The system is very loosely modeled on the powertrain of the first generation Toyota Prius, but is simplified to the point that it can be designed and fabricated by student teams in the course of five semesters. Brief summaries of the projects are given below, but greater details are available from the authors, if desired. Full designs of each component are also available on the authors' wiki site: (available at time of publication). Note that each individual component of the project is relatively small-scale, taking the place of two or three ordinary homework assignments.

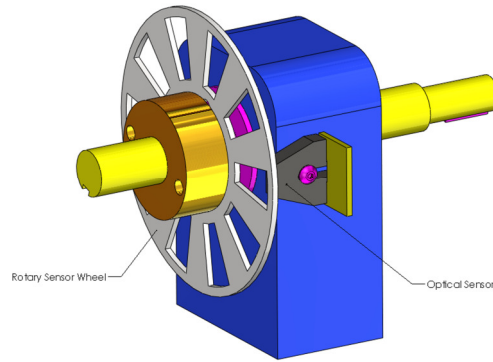


FIGURE 3: TACHOMETER

1. Arduino-Based Tachometer

The first project that students will encounter is the Arduino-based tachometer. This project will take place during the second semester of their sophomore year, in the Mechanical Engineering Laboratory course. The students will experiment with various rotational speed sensor types (Hall Effect, daisywheel, etc.) before designing and fabricating their own tachometers. At the end of this module, students will be able to effectively design and fabricate simple mechatronic sensing devices using the Arduino microcontroller. A sample tachometer design, using a “daisy wheel” and optical sensor, is shown in Figure 3 above.

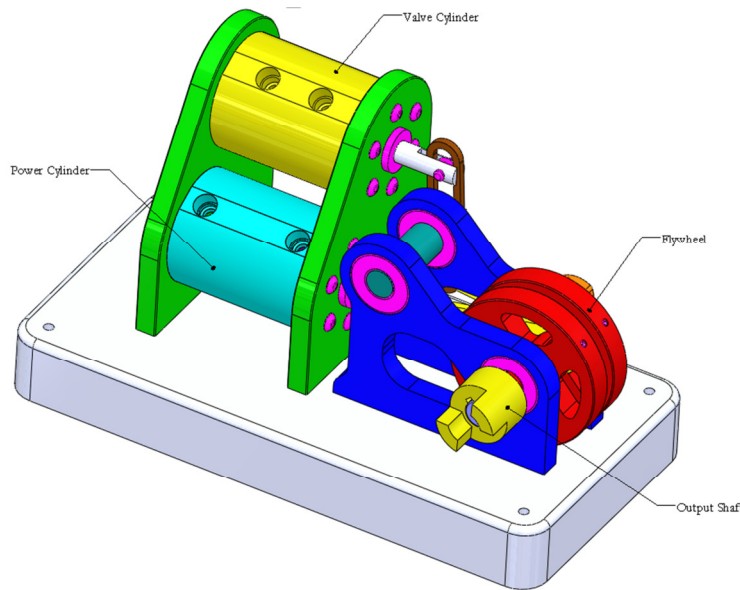


FIGURE 4: THE AIR MOTOR

2. The Air Motor

The air motor will be designed and fabricated as part of the Machine Design and Thermal Sciences I courses. The motor is powered by compressed air from an air tank. The students’ learning outcomes for the project are as follows:

1. Design and fabricate a functioning air-powered reciprocating engine.
2. Use Thermodynamic and Machine Design principles to maximize the efficiency of the engine. This is accomplished through optimization of cylinder bore, stroke length, valve timing and other design variables.

A sample design for an air motor is shown in Figure 4 above. The mechanism for this motor is based on simple steam engine designs and several classes of Rowan University students have successfully completed the air motor project to date.

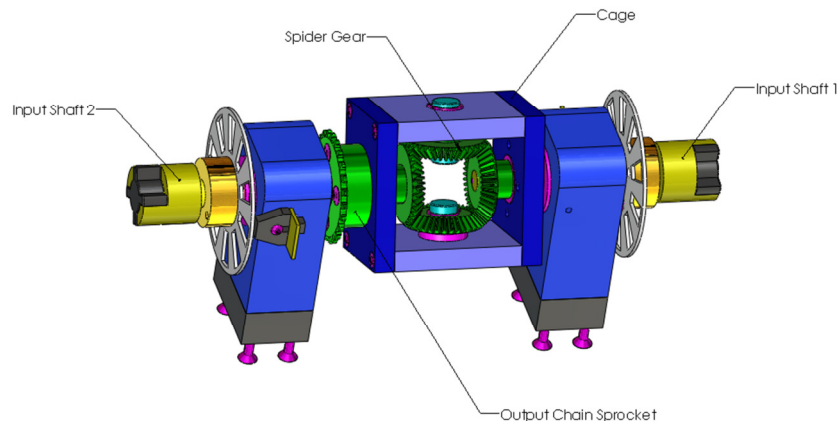


FIGURE 5: PLANETARY GEARSET

3. Planetary Gearset

The learning outcomes of the planetary gearset project are twofold. The primary goal is for students to learn how to design a transmission for specified inputs/outputs. The secondary goal is for students to apply stress analysis techniques to make their gearboxes as small and light as possible.

Since the hybrid powertrain system transmits relatively small loads, the gears and shafts may be made of low strength material, such as nylon. For the differential gearbox project the students will design the gears and spider in SolidWorks 3D CAD software. They will fabricate the gearbox enclosure and other parts in the Rowan Engineering machine shop facility. At the end of the project, the students will test their gearboxes to a specified load limit, with a significant portion of the grade dependent upon the survival of the gears through testing. Credit will also be awarded based upon the strength/weight ratio of the gearboxes.

A sample planetary gearbox design is shown in Figure 5 above. The “differential” design has the advantage of not requiring a large ring gear (lower cost and size) but is constrained to a specified set of gear ratios. A traditional planetary gearset (with sun, planets and carrier) is more versatile, but is more complicated to design and fabricate. Students will be given the choice of topology, but grading criteria will be uniform for all groups.

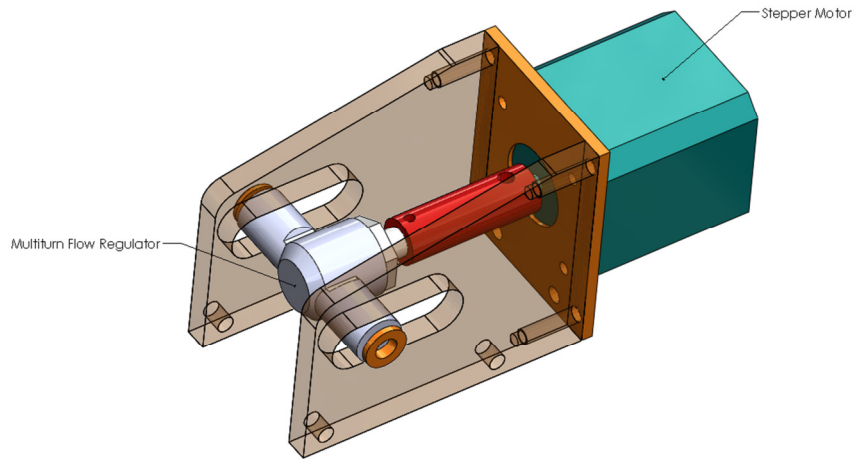


FIGURE 6: THE AIR FLOW REGULATOR

4. Air Flow Regulator

One topic in the Thermal Sciences course sequence is the physics of internal fluid flow. Part of this exploration involves pressure losses and flow control aspects of valves, providing an excellent landscape to design a flow-control valve. To begin this process, students first will investigate existing off-the-shelf valves.

Building on this understanding, the students will have two design options: 1) alter off-the-shelf valves or 2) design new valves to meet the flow control characteristics of the drive train system. To reduce the amount of experimental trial and error, Comsol Multiphysics, a finite element analysis tool, will be used to predict the fluid behavior inside the tortuous path of the throttle valve. The learning outcomes for this exercise are twofold: first, the use of commercial CFD software in design and second, the application of different types of commercially-available valves. Students will be assessed in two categories:

1. Control Valve Design: size, approximate cost, performance (valve sizing coefficient (C_v), valve hysteresis, response time, air motor control, reliability and manufacturability.
2. Experimental Work: the design of experiments, an uncertainty analysis, and the quality of their final report.

A sample flow regulator design is shown in Figure 6 above. Here, a commercial air flow regulator has been coupled with an inexpensive stepper motor, which may be controlled through an Arduino board.

5. DC Motor Speed Control

For the fifth module, students will design and implement a control scheme to maintain constant speed on the DC motor. The control scheme will be implemented using Arduino and the motor speed will be measured using the tachometers fabricated earlier. The learning objective is the use of a simple PID scheme for speed control under variable loading.

6. Overall System Controller

At the end of the fifth semester, all important parts of the hybrid powertrain will have been constructed and tested. It remains only to integrate the components into a complete system. This will be done as the final project in System Dynamics and Control II, a second-semester course in the senior year.

Final integration will require the students to design and test an appropriate system-wide control strategy. Possible student competitions could include tests to see how “far” each team’s power train could travel through a variable drive cycle with a fixed amount of compressed air available. The learning outcome for this module is the design and implementation of a digital controller. This outcome will be assessed through observing the effectiveness of the student controller designs and also the efficiency of their overall hybrid powertrain systems.

Conclusion

Almost all current technological innovation – nanotechnology, advanced transportation, bioengineering – occurs at the intersection of disciplines, and yet engineering education is still delivered in a modular, compartmentalized fashion. To educate the engineer of the 21st century, we should provide students with multidisciplinary design opportunities, *before* their final semester.

This paper describes the use of a long-term sustainable design project to integrate high-level course work in the Mechanical Engineering curriculum. Based upon the latest research, and upon the investigators’ own experience, we believe that this approach has the potential to transform the way undergraduate engineering education is delivered. The modules described here can be adopted (either wholesale or piecemeal) by a wide variety of institutions. More information about the modules can be found at the authors’ wiki site: (will be available at time of publication).

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